THE SENSITIVITY OF ONTARIO LAKE TROUT *(SALVELINUS NAMAYCUSH)* AND LAKE TROUT LAKES TO ACIDIFICATION

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ABSTRACT

Beggs, G.L., J.M. Gunn and C.H. Olver. 1985. The sensitivity of Ontario lake trout (*Salvelinus namaycush*) and lake trout lakes to acidification. Ont. Fish. Tech. Rep. Ser. No. 17: iii & 24 p.

The sensitivity of Ontario's lake trout resource to acidification was examined using data from intensively and extensively studied lake trout lakes.

In a survey of 24 lake trout lakes, spanning a range of water chemistry, it was determined that catch-per-unit-effort of lake trout was reduced in lakes of pH $\leq$5.3 and zero in lakes of pH $<$5.2. The evaluation of age class frequency in the study lakes and a review of the literature suggests that extinction is due to the toxicity of pH and aluminum to the early life history stages of lake trout.

A discriminant function was developed to differentiate between extinct and extant lake trout populations in 173 lakes in the area of Ontario receiving the highest deposition of acidic substances. The function was clearly related to acidification. Inorganic aluminum, estimated from pH, total aluminum and dissolved organic carbon, was the most important variable in the function.

Another discriminant function was developed using only pH. This function was applied to a larger extensive lake trout data set (n=1223) and the results extrapolated to the whole province. It was estimated that lake trout are extinct in 3% of the lakes. When the Sudbury area was removed from consideration due to the large influence of point sources, it was estimated that lake trout are extinct in $<$1% of the remaining lakes.

Survey data from the extensive lake trout lake data set were also extrapolated to the province to examine the sensitivity of the resource. Although many of the confirmed losses of lakes are confined to the Sudbury area it was estimated that 16.2% of lake trout lakes are currently acidified or extremely sensitive to acidic precipitation. This estimate presents a strong argument for continuing work to reduce emissions in order to protect the lake trout resource.

Keywords: lake trout, acidification, pH, aluminum.

THE SENSITIVITY OF ONTARIO LAKE TROUT *(Salvelinus namaycush)* AND LAKE TROUT LAKES TO ACIDIFICATION

INTRODUCTION

In recent years, global attention has been focused on the deposition of strong acids and the resultant acidification of surface waters (Drablos and Tollan 1980, Harvey et al. 1981, Haines 1981). Although it has been only in the past two decades that the acidification problem has been reported in North America (Gorham and Gordon 1963, Schofield 1976), European scientists recognized the phenomenon more than a century ago (Smith 1872).

The most dramatic effect of acidification is the loss of fish stocks. Although a few cases of mass mortality during low pH events have been observed (Leivestad and Muniz 1976), the principal mechanism of fish population loss appears to be successive recruitment failure (Muniz and Leivestad 1980, Haines 1981). Species differ greatly in tolerance to low pH, with many of those of interest to anglers, such as lake trout *(Salvelinus namaycush)*, smallmouth bass *(Micropterus dolomieui)*, and walleye *(Stizostedion vitreum vitreum)* being among the most sensitive (Harvey 1975, Beamish 1976).

While research efforts have expanded in the last decade, little is known about the extent and the rate of change of the fishery resource. Regional estimates of potential loss are important for making decisions on effective management strategies. Minns (1981) first estimated the risk to Ontario's inland fisheries from acidification. He concluded that in Ontario there were over 1200 acidic lakes incapable of sustaining a fish community and that a further 3442 lakes were approaching a similar condition. Lake trout and brook trout *(Salvelinus fontinalis)* were considered to be at greatest risk from acidification.

Using data from intensively and extensively studied lakes we examined Minns' conclusion that acidification poses a threat to the lake trout resource.

THE LAKE TROUT RESOURCE OF ONTARIO

The lake trout is a highly prized fish whose distribution and biology have been extensively studied (Martin and Olver 1976, Martin and Olver 1980, Olver and Martin 1984). It is indigenous only to North America where it reaches its greatest abundance in Ontario, Quebec and the Northwest Territories. In Ontario, less than 1% or 2,218 of an estimated 225,000 lakes (Cox 1978) contain lake trout (Ontario Lake Trout Lakes Geographical Reference Atlas, Olver unpubl.). Although obviously a limited resource, Ontario lake trout lakes comprise a substantial portion (perhaps 20%) of those existing in Canada and indeed the world, a fact which led Martin and Olver (1976) to state, "Ontario has probably the greatest responsibility for this species of any political jurisdiction in the world".

Lake trout lakes are concentrated in three major areas of the province; northwestern Ontario, central Ontario and the Algonquin Highlands in southern Ontario (Fig. 1).

The distribution of lake trout lakes was largely determined by glacial activity. During the Pleistocene, glacial scour deepened many depressions creating favourable lake trout habitat. The deposition of coarse gravels and rocks created spawning grounds. Glacial waters also served as the major dispersal mechanism for lake trout. As a result, lake trout are confined almost exclusively to the recently glaciated lakes of the Canadian Shield with only a few lakes occurring on Paleozoic formations (Fig. 1). A more complete description of the influence of geology on the distribution of lake trout lakes is contained in Appendix A.

Lake trout lakes are generally larger, of higher altitude, deeper, clearer, colder, better oxygenated, lower in alkalinity and total dissolved solids than non-lake trout lakes (Martin and Olver 1976). Ryder and Johnson (1972) characterized these oligotrophic lakes as "swimming pools carved out of granite, with low nutrient tributaries and a cold annual thermal regime". The lake trout attains its greatest abundance in these dilute systems and Ryder (1972) has pointed out that the lake trout is perhaps the most representative index species of an oligotrophic environment.

The lake trout is the only sport fish of economic importance adapted to the deep, coldwater strata of Ontario's oligotrophic lakes. Following its collapse the lake trout is not replaced by any other species which fulfills a similar role in the fish community or provides a comparable angling opportunity. Additionally, lake trout indigenous to these Canadian Shield systems have evolved over several thousand generations, in some cases to become genetically discrete stocks (P. Ihssen, pers. comm.). Acidification of lake trout systems may not only result in the loss of fisheries but also reduction in genetic diversity and the extinction of unique gene pools.

METHODS

To determine the response of lake trout communities to acidification, 24 lakes that were known to contain lake trout (documented in historical surveys, reliable conservation officer and angler reports) and spanned a range of water chemistry were surveyed between May and September of 1982 or 1983. The lakes are located in secondary watersheds 2B, 2C, 2D, and 2J (Fig. 2).

1	BLACK BEAVER	9	BIGWOOD	17	FLORENCE
2	NORTH HUBERT	10	BOWLAND	18	PILGRIM
3	HUBERT	11	LAUNDRIE	19	BLUESUCKER
4	BARBARA	12	REGAN	20	SEAGRAM
5	GREY OWL	13	WHITEPINE	21	IRON
6	BURNS	14	LULU	22	THREE NARROWS
7	REGAL	15	MARINA	23	LUMSDEN
8	MICHAUD	16	JERRY	24	GEORGE

Figure 2. Location of lakes in the comparative netting survey.

A standard capture effort of 6 overnight sets of 76.2 m monofilament gill nets (15.2 m panels of 2.5, 3.8, 5.1, 6.3, 7.6 cm stretched mesh) was used on each lake. In addition, the inshore fish community was assessed using 6 24-hour sets of both 1.22 m trapnets with 0.6 cm mesh (Beamish 1972) and plexiglass minnow traps (Casselman and Harvey 1973, Tripple and Crossman 1981).

Catch-per-unit-effort (C.U.E. as number or weight 100m-hr^{-1}) for the gill nets was used as an index of relative abundance. Number of species present was determined from all types of gear. Length and age composition of the lake trout samples were used to determine if recruitment was occurring in these lakes.

From 1979 through 1982 water samples were collected (as integrated tube or volume-weighted whole lake samples) from 1,223 lake trout lakes and these data were compiled with information about lake location (latitude, longitude and watershed code (Cox 1978)) in an extensive lake trout lake data set. All water samples were analyzed to determine pH, conductivity and inflection point alkalinity. Water samples from a subset of 225 lakes were also analyzed for major cations, anions, nutrients and metals. Chemical analyses were conducted according to methods outlined by the Ontario Ministry of the Environment (MOE 1979, MOE 1981a), and Goodchild et al. (1981).

Metal levels are expressed as total unfiltered concentrations. In addition, because of the toxicological importance of inorganic monomeric aluminum (Driscoll et al. 1980), levels of this form of aluminum were estimated from measured total aluminum using three separate regression equations developed for four Dorset area Lakes (B. Lazerte, pers. comm.):

$$Al_1 = 267.0 + 98.7\ Al_T - 46.0\ pH,$$

$$Al_2 = 331.4 + 100.1\ Al_T - 55.8\ pH - 3.2\ DOC,$$

$$Al_3 = 408.0 + 742.0\ Al_T - 71.6\ pH - 37.9\ DOC - 128.5\ Al_T\ pH + 7.2\ pH\ DOC,$$

where, Al_1, Al_2, and Al_3 = calculated inorganic monomeric aluminum ($\mu g\ l^{-1}$),

Al_T = total aluminum ($mg\ l^{-1}$), and

DOC = dissolved organic carbon ($mg\ l^{-1}$).

Negative values of inorganic aluminum were assumed to indicate that no aluminum was present in this form and zero values were assigned to those lakes.

The data from the 225 lake trout lakes that were sampled for the full range of chemistry were combined with physical descriptors including lake location, altitude, surface area, mean depth, Secchi depth and distance from Sudbury to form the intensive lake trout lake data set. The information in this data set is summarized in Table 1. The reproductive status of each lake in the set was categorized from test netting and/or creel survey records as viable (self-sustaining population, n=180 lakes), extinct (functionally extinct: may contain a few large relict lake trout, n=27 lakes) or unknown (n=18 lakes).

The distribution of each descriptor variable in the data set was tested for normality and some variables were transformed. Secchi depth, area, distance from Sudbury, and apparent colour were $\log_e$ transformed, reciprocal transformations were applied to Ca and Mg, and square root transformations to DOC and NH_3. Two subsets of this intensive data

Table 1. Summary of physical and chemical information on 225 Ontario lake trout lakes in the intensive lake trout lake data set.

Variable	No. of lakes	Median	Mean	Range
pH	221	6.30	6.12	4.0 - 8.11
conductivity ($\mu S\ cm^{-1}$)	222	41	45.1	18 - 144
alkalinity ($mg\ l^{-1}$)	222	2.1	5.0	-2.7 - 67.7
Ca ($mg\ l^{-1}$)	197	3.4	4.5	1.6 - 25.7
Mg ($mg\ l^{-1}$)	196	0.9	1.2	0.4 - 5.4
Na ($mg\ l^{-1}$)	178	0.9	1.0	0.4 - 4.3
K ($mg\ l^{-1}$)	178	0.4	0.4	0.3 - 1.3
SO_4 ($mg\ l^{-1}$)	179	10.5	10.8	4.5 - 19.0
Cl ($mg\ l^{-1}$)	165	0.4	0.8	0.2 - 6.5
DOC ($mg\ l^{-1}$)	161	3.1	3.3	0.1 - 13
DIC ($mg\ l^{-1}$)	162	1.0	1.7	0.2 - 18
TKN ($mg\ l^{-1}$)	167	0.19	0.20	0.05 - 0.62
NH_3 ($mg\ l^{-1}$)	156	0.03	0.03	0.00 - 0.12
NO_3 ($mg\ l^{-1}$)	153	0.03	0.05	0.005 - 0.42
NO_2 ($mg\ l^{-1}$)	156	0.001	0.001	0.001 - 0.004
TP ($mg\ l^{-1}$)	190	0.006	0.007	0.001 - 0.030
Zn ($\mu g\ l^{-1}$)	180	4	6	1 - 31
Cu ($\mu g\ l^{-1}$)	189	2	2	1 - 30
Ni ($\mu g\ l^{-1}$)	187	2	6	5 - 58
Pb ($\mu g\ l^{-1}$)	157	3	3	0 - 12
Fe ($\mu g\ l^{-1}$)	177	40	70	0 - 550
Mn ($\mu g\ l^{-1}$)	197	20	48	1 - 272
Al ($\mu g\ l^{-1}$)	197	38	73	2 - 840
colour (Hazen units)	182	10.3	14.4	-3.2 - 81.4
Secchi (m)	196	6.2	6.9	1.5 - 23.4
distance from Sudbury (km)	152	83	97.5	21 - 261
altitude (m)	66	358	342.5	140 - 467
area (ha)	215	209	741.5	5.2 - 21,578.9
mean depth (m)	73	10.0	12.0	3.7 - 38.1

set were analyzed using multivariate techniques. The first subset contained 173 of the 225 lakes in the intensive data set. They are located in an area of Ontario that is currently receiving the highest deposition of acidic substances (weighted mean annual precipitation pH < 4.5 [Fig. 3]). This area of highest deposition is delineated by longitudes 7820 and 8340 and latitudes 4510 and 4755. All 27 of the lakes with extinct lake trout populations occur in this restricted subzone.

The second subset, called the Sudbury subzone, is located within the first subset between longitudes 8000 and 8130 and latitudes 4600 and 4730 (Fig. 3). Lakes within this Sudbury subzone are not only receiving high deposition of acidic precipitation from long range transport, but are also affected by local emissions from the metal smelting industry.

To examine the factors which distinguish between viable and extinct lake trout lakes, we used stepwise discriminant function analysis (Klecka 1975) on the 173 lake subzone of highest deposition. The discriminant function was then used to classify all lakes within the intensive data set (n=225). The *a posteriori* classification of lakes of known population status was used as a measure of the discriminating power and classification accuracy of these functions. Application of functions to lakes of unknown status allowed us to predict population status in lakes for which we had no netting records.

Figure 3. The location of subzones used in analysis of the intensive lake trout data set.

We also performed a stepwise discriminant analysis on lakes within the Sudbury subzone to examine the significance of metals in distinguishing extinct from viable lake trout lakes.

The current chemical status of the 1223 lakes within the extensive data set was examined with respect to two indices of acidification - alkalinity and pH. A discriminant function developed from the intensive lake trout data set was used to classify the lakes in the extensive data set and estimate the number of lake trout populations lost due to acidification. Numbers of acidified and extinct lake trout lakes within the sample were extrapolated to provide estimates for the province.

RESULTS AND DISCUSSION

LAKE TROUT RESPONSE TO ACIDIFICATION

Comparative Netting Survey

The data from our survey of lake trout lakes of varying water chemistry illustrate the response of lake trout populations to lake acidification.

Study Lakes

The physical and chemical characteristics of the intensively studied lake trout lakes are presented in Table 2. Surface area and maximum depth ranged from 21 to 1002 ha and 17 to 78 m, respectively. With the exception of one high pH lake, Regan Lake, used as a reference, all test netting lakes had summer epilimnetic pH levels between 4.8 - 5.8. A pH of 6.0 was estimated from the results of previous studies (Beamish 1976, Gunn 1980a) as a level above which acidification effects on lake trout were not usually evident, or at least, could not be readily isolated from responses to other stresses. Additional data are available from longterm studies on several of these lakes (Beamish et al. 1975, Gunn 1980b, Gunn and Keller 1984a).

Community Effects

Acidification affects the entire fish community of lake trout lakes. As a lake acidifies, sensitive species such as walleye, burbot *(Lota lota)*, smallmouth bass and lake trout decline and may become extinct (Beamish et al. 1975, Kelso and Gunn 1984). Relatively resistant species such as yellow perch *(Perca flavescens)* generally persist, and may even prosper temporarily, but with continued deterioration in water quality even these species disappear (Beamish 1976, Ryan and Harvey 1980). The entire fish assemblage, which in 1960 included lake trout, brook trout and

Table 2. Physical and chemical characteristics of 1982-83 test netting lakes. Some measures of community composition, relative abundance, and lake trout status are presented.

pH[a]	Lake Name	Lat/Long	Surface Area (ha)	Max. Depth (m)	Secchi Depth (m)	Colour (Hu)	T.I. Alk. ($mg\ l^{-1}$)	Cond ($\mu S\ cm^{-1}$)	Total Al ($\mu g\ l^{-1}$)	Number of Species	C.U.E.[b] (no. $100m\text{-}hr^{-1}$) Native L. Trout	C.U.E. (no. $100m\text{-}hr^{-1}$) Stocked L. Trout	C.U.E. (kg $100m\text{-}hr^{-1}$) All Species	Native Lake Trout Status[d]
4.84	Florence	4715/8033	1007	38	6.5	6.8	-.86	39	280	8	.000	c	.020	extinct
4.92	Lumsden	4601/8126	21	22	8.7	-.5	-.58	25	190	1	.000	-	.001	extinct
4.92	Jerry	4722/8039	56	35	11.0	-.7	-.54	32	210	0	.000	-	.000	extinct
5.05	Bowland	4705/8050	108	28	6.5	.9	-.40	34	130	1	.000	.033	.012	extinct
5.22	Marina	4724/8040	37	17	7.2	8.2	-.28	30	100	4	.030	-	.356	fair
5.23	Laundrie	4707/8052	375	20	4.5	15.9	-.10	33	80	3	.000	.390	.539	extinct
5.30	Barbara	4716/8420	58	45	10.6	5.8	-.28	18	100	1	.000	.058	.058	extinct
5.31	Grey Owl	4716/8412	248	31	7.1	11.2	-.04	20	83	0	.000	-	.000	extinct
5.33	Pilgrim	4711/8041	123	25	8.8	14.1	-.26	29	45	3	.801	-	.450	good
5.33	Seagram	4706/8032	102	19	6.0	11.2	.05	47	140	9	.157	-	.857	fair
5.33	Bluesucker	4710/8036	144	21	8.0	-.3	-.19	32	100	7	.288	-	.444	fair
5.40	Black Beaver	4724/8430	166	40	7.2	7.1	.00	19	72	2	.187	-	.484	fair
5.45	Lulu	4724/8045	81	23	5.5	17.0	-.13	29	84	5	.029	-	.070	remnant
5.49	George	4602/8124	182	40	12.5	0.2	.70	35	80	9	.025	.025	.804	remnant
5.50	Bigwood	4651/8105	266	58	7.0	16.1	.41	37	81	7	.210	-	.272	good
5.58	North Hubert	4720/8427	34	38	11.2	3.6	-.08	18	67	3	.407	-	.638	fair
5.58	Hubert	4719/8427	85	38	8.9	4.9	-.03	19	61	3	.230	-	.476	fair
5.63	Michaud	4649/6114	148	24	7.0	8.1	.52	35	94	5	.077	-	.246	remnant
5.64	Whitepine	4717/8050	67	22	8.0	7.1	.57	34	60	4	.059	.588	.402	remnant
5.74	Iron	4657/8021	72	27	10.2	-.5	.12	42	38	7	.807	.115	.697	good
5.74	Three Narrows	4605/8128	948	52	7.4	.8	.02	31	51	14	.107	-	.605	fair
5.76	Burns	4636/8307	166	78	21.0	3.0	.03	24	23	5	.948	-	.576	good
5.62	Regal	4636/8305	32	17	9.0	-.1	.12	25	35	5	.198	-	.193	fair
7.08	Regan	4714/8047	122	38	8.3	2.4	3.76	42	8	9	.645	-	.436	good

[a] - the water chemistry is from epilimnetic tube composite samples taken at mid-lake during summer stratification, 1982-83. Collection and analysis by Ontario Ministry of the Environment (MOE).

[b] - the C.U.E. (catch-per-unit-effort) is a measure of relative abundance derived from standard gill net (2.5 - 7.6 cm mesh) catches during 1982-83.

c - stocked but no survival

d - extinct - may still contain a remnant population.
remnant - small population of large adults exhibiting recruitment failure.
fair - relatively sparse population with regular or sporadic recruitment.
good - relatively abundant reproducing population.

white sucker (*Catostomus commersoni*), perished in Jerry Lake (currently pH 4.9, Table 2). In Lumsden Lake (present pH 4.9) 7 species of fish disappeared between 1960 and 1970 as the lake acidified (Beamish and Harvey 1972), leaving only a tiny population of lake chub (*Couesius plumbeus*). Other examples of severe effects on the fish community include: Laundrie Lake (present pH 5.2) in which longnose sucker (*Catostomus catostomus*), white sucker and native lake trout are now extinct, while a large population of yellow perch persists (Kelso and Gunn 1984); and George Lake (pH 5.5), where during the 1960s and 1970s walleye and smallmouth bass became extinct and lake trout were reduced to a remnant population (Beamish et al. 1975).

In the experimental acidification of Lake 223 in northwestern Ontario, Mills (1984) found similar community effects to those observed in natural populations affected by acid precipitation. During the progressive acidification of the lake, the cyprinids were the first to respond, with fathead minnows (*Pimephales promelas*) disappearing rapidly at pH 5.6 to be replaced in dominance by pearl dace (*Semotilus margarita*). Recruitment failure in lake trout and white sucker occurred as the acidification was continued, at pH 5.4 and 5.1, respectively.

The impact of acidification on the standing crops of all fish in our comparative survey lakes is demonstrated by ordering relative abundance (combined-catch-per-unit-effort from the lake trout test netting lakes) by pH (Table 2). The catch-per-unit-effort (kg 100m-hr^{-1}) of all species declines rapidly below a pH of 5.2 (Fig. 4).

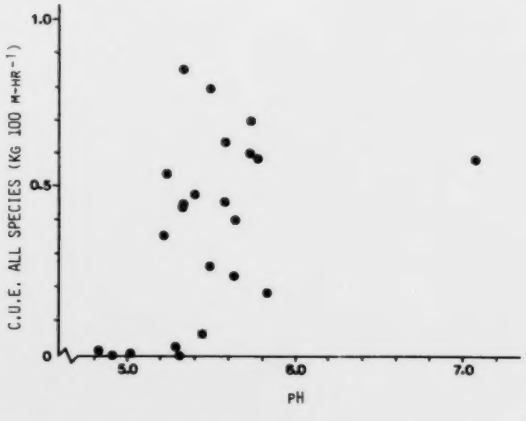

Figure 4. The relationship between catch-per-unit-effort (kg 100 meter-hours^{-1}) of all species in the comparative survey lakes and mid-lake, summer, epilimnetic pH.

Population Effects

Acidification causes a reduction in lake trout recruitment success. Because of the relatively stable recruitment pattern and longevity of lake trout (Martin and Olver 1980), this effect is seen as omissions or reductions in year class strength. Eventually recruitment fails completely resulting in a population composed of old fish and ultimately extinction (Beamish et al. 1975, Kelso and Gunn 1984).

Examples from our test netting survey (Table 2, Fig. 5) illustrate these population effects. Lake trout were extinct in: Florence (pH 4.8), Lumsden (pH 4.9), Jerry (pH 4.9), Bowland (pH 5.0), and Laundrie (pH 5.2) lakes. While we failed to capture lake trout in Grey Owl (pH 5.3) and Barbara (pH 5.3) lakes, the evidence that naturally reproducing populations existed in these lakes is only anecdotal. George (pH 5.5) and Michaud (pH 5.6) lakes contained only remnant populations of large old lake trout. On Regan Lake, the pH 7.1 reference lake, the gill net catch consisted of an even distribution of sizes and ages, typical of unstressed lakes.

In one unusual case, Whitepine Lake (pH 5.6), the remnant population has recently begun to recruit successfully. Whitepine Lake, located 90 km north of Sudbury, has been extensively studied by Gunn and Keller (1984a). They speculated that water quality improvements produced by recent reductions in emissions from the metal smelters at Sudbury (MOE 1982), may be responsible for the recovery in the native lake trout population.

From the limited literature on the toxicity of hydrogen and aluminum ions to lake trout (summarized in Table 3) it appears that

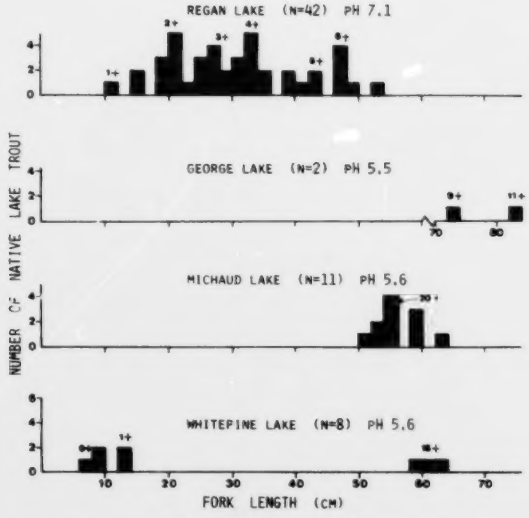
REGAN LAKE (N=42) PH 7.1
GEORGE LAKE (N=2) PH 5.5
MICHAUD LAKE (N=11) PH 5.6
WHITEPINE LAKE (N=8) PH 5.6
NUMBER OF NATIVE LAKE TROUT
FORK LENGTH (CM)

Figure 5. The distribution of lengths of native lake trout in four comparative survey lakes.

Table 3. Some observed effects of pH and Al on lake trout.

pH	Total Al ($\mu g\ l^{-1}$)	Inorganic Al ($\mu g\ l^{-1}$)	Lake trout observations (reference)
6.0 - 7.4	na	na	includes 86% of Ontario's viable lake trout populations (Martin and Olver 1976)
5.6	49	na	recruitment resumes in Whitepine Lake (Gunn and Keller 1984a)
$\leq$5.5	na	na	reproductive failure in La Cloche lakes (Beamish 1976)
5.4	171	na	no effect on survival but reduced growth of sac fry in comparison to fry in neutralized water (Gunn and Keller 1984b)
5.4	na	na	recruitment failure in artificially acidified Lake 223 (Mills 1984)
5.2	80	50*	good C.U.E. of stocked yearlings in Laundrie Lake (see Table 2)
5.0	130	na	low C.U.E. of stocked yearlings in Bowland Lake (see Table 2)
5.0	na	na	no effect on fecundity and egg size (Polkinghorne 1980)
$\leq$5.0	na	na	extinction of populations in La Cloche lakes (Beamish 1976)
4.8	280	260*	no survival of stocked fingerlings in Florence Lake (see Table 2)
4.7	135	na	155 hr median survival time of early juveniles (MNR unpubl. data)
4.6	490	410*	no survival of sac fry in Ruth-Roy Lake bioassay (Gunn and Keller 1984b)
4.5	180	50	18% mortality of sac fry during low pH depression on spawning site (Gunn and Keller 1984a)
<4.0	nil	nil	LC50 for sac fry (W. Kwain, pers. comm.)

* - estimated values
na - not available

recruitment may be affected during several stages, at hatching, sac fry or early juvenile life history stages.

Remnant lake trout populations continue to spawn at pH 5.1 (Gunn 1980b) and egg number and size are within the normal range at pH 5.0 (Polkinghorne 1980). Little mortality occurs during the egg stage. Survival of lake trout eggs that were fertilized, hardened and incubated in Bowland Lake at pH 5.0 and total aluminum concentration 130 µg l^{-1} (conditions lethal to yolk sac fry and juveniles), was 92% (Gunn, unpubl. data).

During *in situ* bioassays in George Lake, Gunn and Keller (1981) observed that many of the mortalities occurred at hatching. After hatch, lake trout sac fry may also be vulnerable because of their relative immobility to the episodic flushing of acidic meltwater through nearshore, shallow spawning sites. Gunn and Keller (1984a) found that mortality (18%) of sac fry held in incubators above a spawning ground, occurred during peak runoff when pH was reduced to 4.5 and inorganic aluminum concentrations reached 50 µg l^{-1}. In the absence of aluminum, Kwain (pers. comm.) found that the 96 hour lethal concentration for 50% (96 hr LC50) of lake trout sac fry was less than pH 4.0.

Alevin lake trout (emergence - feeding) are tolerant of total aluminum concentrations as high as 222 µg l^{-1} at pH 5.2 (Gunn and Keller 1981). However, in experimentally acidified Lake 223, Mills (1984) found that survival of lake trout to catchable size ceased when lake pH was reduced to 5.4. He suggested that mortality of the early juvenile stage was responsible as little mortality of egg and sac fry stages was observed in bioassays conducted in Lake 223.

Stocking assessment studies suggest that the critical water quality requirements for survival of yearling lake trout occur between the conditions found in two of our comparative survey lakes; Laundrie (pH 5.2, total Al 80 µg l^{-1}) and Bowland (pH 5.0, total Al 130 µg l^{-1}). Stocking was successful in Laundrie while few if any stocked lake trout survived in Bowland (Table 2). Although the pH in these lakes differs by less than 0.2 units, the concentration of aluminum is higher in Bowland. Additionally, Laundrie has more highly coloured water than Bowland (15.9 and 0.9 Hazen units, respectively), suggesting that more of the measured aluminum in Bowland Lake is in the inorganic form and not bound in nontoxic organic complexes (Baker and Schofield 1980, Driscoll et al. 1980).

The relative abundance of native lake trout in the test netting lakes [C.U.E. (number)] declined markedly in lakes with pH $\leq$ 5.3 (Fig. 6). Total extinction of native lake trout occurred in lakes with pH < 5.2.

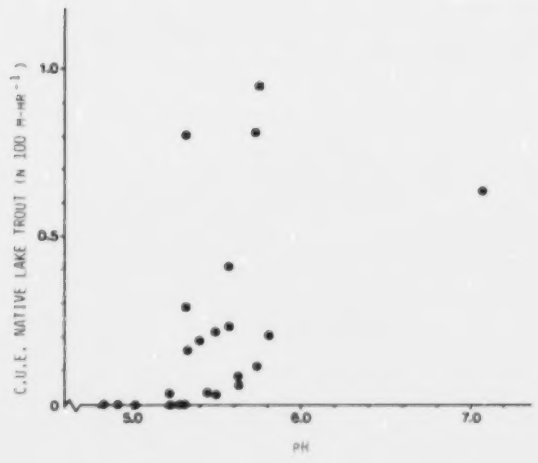

Figure 6. The relationship between catch-per-unit-effort (number 100 meter-hours^{-1}) of native lake trout in the comparative survey lakes and mid-lake, summer, epilimnetic pH.

From the results of studies cited in the literature and our own test netting data we suggest that a pH $\geq$ 5.5 and total aluminum concentrations < 50 µg l^{-1} are necessary to ensure maintenance of naturally reproducing lake trout populations.

ANALYSIS OF FACTORS ASSOCIATED WITH THE EXTINCTION OF LAKE TROUT

Through the use of stepwise discriminant function analysis we determined the characteristics which best differentiate viable from extinct lake trout lakes in the intensive lake trout lake data set. Results of the analysis are summarized in Table 4. The function was able to distinguish viable from extinct lake trout lakes (Wilk's $\lambda = 0.206$, $\chi^2 = 169.9$, df = 9, and $P < 0.001$). The variables that contributed the most to our ability to discriminate between viable and extinct lake trout lakes, in order of decreasing importance, were: Al_2, Al_3, reciprocal Ca, reciprocal Mg, Fe, log apparent colour, Mn, NO_3, and log distance from Sudbury (Table 4). Other variables (Table 1) were not selected for the function as they contributed little to the ability to discriminate between the two groups.

The inclusion of the variables Al_2, Al_3, Mn, Ca, colour and distance from Sudbury in the function suggests that extinction of lake trout populations is related to surface water

Table 4: Results of stepwise discriminant analysis. Variables listed in order of decreasing importance. Group means for viable and extinct lakes in parentheses (Viable, Extinct).

Loading Zone D		Sudbury Subzone		Loading Zone D	
Al_2	(3.37, 77.66)	Al_2	(7.51, 77.66)	pH	(6.48, 4.87)
Al_3	(3.43, 86.38)	Al_3	(7.07, 86.38)	alkalinity	(5.72, -0.80)
1/Ca	(0.29, 0.36)	1/Ca	(0.29, 0.36)	conductivity	(45.16, 38.93)
1/Mg	(1.02, 1.30)	1/Mg	(1.00, 1.30)		
Fe	(0.08, 0.06)	log Secchi	(0.81, 1.01)		
log colour	(1.20, 0.95)	conductivity	(46.77, 39.63)		
Mn	(0.03, 0.17)	NO_3	(0.03, 0.08)		
NO_3	(0.05, 0.08)	Fe	(0.09, 0.06)		
log distance	(1.96, 1.80)				

acidification. The toxicity of aluminum, particularly the inorganic monomeric form, to fish, has been reported by Schofield (1977), Baker and Schofield (1980) and Driscoll et al. (1980).

Although work done to date suggests that Mn does not reach toxic levels in acidic lakes, Lockhart and Lutz (1977) found a forty-fold increase in skin Mn concentration in white suckers from acid-stressed lakes. They postulated that elevated skin Mn levels might interfere with skin Ca absorption. Additionally, the toxicity of Mn has not been exhaustively investigated in very dilute waters and Mn may act synergistically with other metals (Lewis et al. 1979).

Wright and Snekvik (1978) found that Ca was the most important ion determining fishery status in Norwegian lakes. Brown (1981) demonstrated that the toxicity of hydrogen ion to juvenile brown trout (*Salmo trutta*) could be reduced by increasing water Ca concentration. The role of ambient Ca in mediating the effects of low environmental pH is reviewed in Wood and McDonald (1982).

In the intensive data set, extinct lakes tend to be less coloured than viable lakes (Table 4), although both groups are low in colour. Driscoll et al. (1980) described the reduction in toxicity of dissolved aluminum when it was complexed with organic ligands. Colour is often considered a surrogate indicating the presence of organic acids.

The inclusion of distance from Sudbury in the function suggests that the emissions from the metal smelting complex at Sudbury have contributed to the loss of fish stocks from the region's lakes.

As Fe, Mg and NO_3 can be altered in acidified systems, their inclusion in the function supports our hypothesis that extinction of lake trout in these lakes is related to acidification.

A posteriori classification correctly assigned 96.9% of the lakes of known population status. Six of 12 lakes of unknown population status, with all 9 discriminating variables present, were classified as extinct.

Green (1979) argued that in multivariate analysis, the interpretation of the significance of the variables selected and their rank of order of importance is meaningless if the variables are correlated. As many of our variables are highly correlated, we examined group separation on the basis of Al_2 only. Our current understanding of the mechanism of fish loss from acidic lakes suggests that this variable, which is a function of pH, total Al, and DOC, should provide good group separation if the differences between extinct and viable lake trout lakes is related to acidification.

The function separated extinct and viable lake trout lakes (Wilk's $\lambda = 0.238$, $\chi^2 = 204.49$, df = 1, $p < 0.001$) and correctly classified 96.5% of the lakes of known population status *a posteriori* providing further support for our hypothesis.

The results of the discriminant analysis to investigate the role of metals in the extinction of lake trout in lakes within the Sudbury subzone (Table 4) were quite similar to the previous analysis. Of the 55 lakes used to develop the function, 39 contained viable lake trout populations and in 16, lake trout were extinct. Significant differences were found between centroids of extinct and viable groups (Wilk's $\lambda = 0.2074$, $\chi^2 = 77.08$, df = 8, $p < 0.001$) and 93.7% of the lakes of known population status were correctly classified using this function. Variables selected to distinguish extinct and viable lake trout lakes (listed in order of decreasing importance) included: Al_2, Al_3, reciprocal Ca, reciprocal Mg, log Secchi, conductivity, NO_3, and Fe. The rationale for derivation of this function again appears to be related to the toxicity of these waters to lake trout (Al_2, Al_3, reciprocal Ca) as well as to the more general characteristics of acidic lakes (i.e. increased Secchi transparency, MOE 1978, Scheider et al. 1979).

Again we tested the ability of a function containing only Al_2 to distinguish viable from extinct lake trout lakes. Although the function discriminated between the two lake types, we found that the proportion of lakes correctly classified improved (from 89.7% to 92.4%) when Ca was added to the function (Wilk's $\lambda = 0.267$, $\chi^2 = 83.12$, df = 2, $p < 0.001$).

Both copper and nickel were not selected for use in the discriminant function. The contribution of these metals to extinction of lake trout populations may be less important than that of aluminum. Alternatively, by relating historical fisheries extinctions to water chemistry data collected in 1981, we may be underestimating or overestimating the possible contributions of elements that may have changed in concentration since the time of lake trout extinction. For example, in a set of low pH lakes in the Sudbury area, the concentration of copper declined by 50% in a 7 year interval between sampling, 1974-76 to 1981-83 (Keller and Pitblado, unpubl. ms.). In addition, between 1973 and 1979, levels of copper and nickel in Clearwater Lake, near Sudbury, were the lowest in 1978 and 1979 (Yan and Miller 1982). These lower concentrations can be attributed to reduced deposition (Scheider et al. 1981).

A third discriminant analysis was performed using only the chemical variables (pH, alkalinity, conductivity) for which data were available in the larger extensive lake

trout lake data set. All three variables were used in the function to discriminate between extinct and viable lake trout lakes (Wilk's λ = 0.4198, χ^2 = 145.39, df = 3, p <0.001)(Table 4). The function correctly classified 95.3% of the lakes.

CURRENT CHEMICAL STATUS OF ONTARIO LAKE TROUT LAKES

The location of Ontario lake trout lakes and secondary watersheds in relation to current loadings of acid is illustrated in Fig. 7. The precipitation pH isopleths (weighted mean annual pH) have been taken from Minns (1981) who adjusted them southwards to conform to secondary watershed boundaries. Their location divides Ontario into four deposition zones:

A) northwest of pH 5.5 isopleth
B) between pH 5.0 and 5.5 isopleths
C) between pH 4.5 and 5.0 isopleths
D) southeast of pH 4.5 isopleth.

The southward adjustment of isopleths results in conservative estimates of loadings compared to recent Ontario data (Chan et al. 1983).

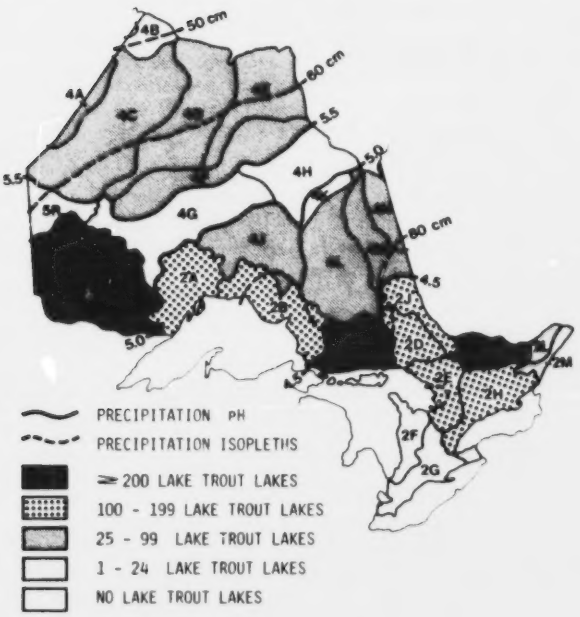

Figure 7. The number of lake trout lakes in secondary watersheds in Ontario relative to precipitation pH and annual precipitation isopleths.

A large proportion of the lake trout resource (55%) occurs in the south and central portions of Ontario. These areas receive the most precipitation annually (80 - 100 cm) and precipitation of the lowest pH (<4.5), and hence the highest loadings of acid (>20 kg wet sulphate ha^{-1}).

As well as receiving very high deposition of acidic substances, the physical characteristics of many lake trout lakes, (high altitude, headwater lakes in small watersheds with shallow overburden and bedrock of low acid-neutralizing capability) are those reported to be related to acidification and the loss of fisheries in other areas of the world (Schofield 1976, Dickson 1980). Ontario lake trout lakes therefore appear to be a resource at risk from acidification.

By examining the distribution of lakes sampled chemically (referred to as the extensive lake trout lake data set) we can assess the current status of the lake trout resource. The distribution of the lakes in the extensive data set, relative to the distribution of known lake trout lakes, is shown by secondary watershed within each loading zone in Table 5. None of the 28 lakes in the most northern loading zone (A) were sampled, but they are not likely to be affected by acid precipitation because of their distance from emission sources and their geological setting. The lakes in loading zone B have not been sampled at a frequency that reflects their abundance in the province. Sampling was concentrated in the most southern loading zone (D) where 55% of the lake trout lakes occur and where the impact of acid precipitation is likely to be most severe (weighted mean annual precipitation pH <4.5). The sample size increased progressively within each loading zone from A to D and was approximately 0, 23, 55 and 73% of the known lake trout lakes, respectively (Fig. 8).

Distribution of Lakes by Alkalinity Class

Lakes have been subjectively categorized into the following five sensitivity (to acidification) classes based on alkalinity levels (MOE 1981b):

Acidified	< 0 mg l^{-1}
Extreme sensitivity	0 - 1.99 mg l^{-1}
Moderate sensitivity	2.00 - 9.99 mg l^{-1}
Low sensitivity	10.00 - 24.99 mg l^{-1}
Not sensitive	≥ 25 mg l^{-1}

With the exception of lakes in watersheds 2L and 2M, the lakes in loading zone D are more sensitive to acidification than lakes in loading zones B and C (Table 6). When Sudbury and non-Sudbury subzones are combined, approximately 8% of the lakes sampled in loading zone D are acidified and 22% are in the extreme sensitivity class.

Table 5. Distribution of known lake trout lakes in geographical reference atlas and lake trout lake data set by secondary watershed within loading zones.

Loading zone	Watershed	No. of lakes in atlas	No. of lakes in extensive data set	Sample size (%)
A	4A	3	0	0.0
	4C	17	0	0.0
	4D	2	0	0.0
	4E	4	0	0.0
	4F	2	0	0.0
	TOTAL	28	0	0.0
	%	1.3	0.0	
B	4G	50	6	12.0
	5P	367	108	29.4
	5Q	206	39	18.9
	5R	37	2	5.4
	TOTAL	660	155	23.5
	%	29.7	12.7	
C	2A	105	49	46.7
	2B	146	96	65.8
	4J	13	8	61.5
	4L	22	8	36.4
	4M	21	9	42.9
	4N	1	0	0.0
	TOTAL	308	170	55.2
	%	13.9	13.9	
D	2C	418	276	66.0
Non-	2D	25	19	76.0
Sudbury	2E	134	129	96.3
	2F	1	0	0.0
	2H	130	97	74.6
	2J	97	58	59.8
	2K	218	137	62.8
	2L	5	3	60.0
	2M	23	8	34.8
	SUBTOTAL	1051	727	69.2
	%	47.4	59.4	
Sudbury[1]	2C	53	53	100.0
	2D	94	94	100.0
	2J	24	24	100.0
	SUBTOTAL	171	171	100.0
	%	7.7	14.0	
	TOTAL	1222	898	73.5
	%	55.1	73.4	
GRAND TOTAL		2218	1223	55.1

[1]Lakes, in the vicinity of Sudbury, known to be affected by smelter emissions.

Table 6. Alkalinity class of lakes in extensive lake trout lake data set by secondary watershed within loading zones B, C, D.

Loading zone	Watershed	Alkalinity Class: Acidified	Extreme sensitivity	Moderate sensitivity	Low sensitivity	Not sensitive	Total
B	4G	0	0	2	3	1	6
	5P	0	1	78	22	7	108
	5Q	0	0	17	14	8	39
	5R	0	0	1	1	0	2
	TOTAL	0	1	98	40	16	155
	%	0.0	0.7	63.2	25.8	10.3	
C	2A	0	0	5	23	20	48
	2B	4	17	33	18	24	96
	4J	0	0	0	1	7	8
	4L	0	0	1	2	5	8
	4M	0	0	0	2	7	9
	TOTAL	4	17	39	46	63	169
	%	2.4	10.1	23.0	27.2	37.3	
D	2C	7	52	179	22	6	266
Non-	2D	0	2	11	6	0	19
Sudbury	2E	1	43	81	3	0	128
	2H	0	15	42	19	20	96
	2J	1	5	27	18	7	58
	2K	0	22	90	13	8	133
	2L	0	0	0	0	2	2
	2M	0	0	0	2	4	6
	TOTAL	9	139	430	83	47	708
	%	1.3	19.6	60.7	11.7	6.6	
Sudbury	2C	15	21	10	3	2	51
	2D	37	19	28	10	0	94
	2J	7	11	5	1	0	24
	TOTAL	59	51	43	14	2	169
	%	34.9	30.2	25.4	8.3	1.2	
GRAND TOTAL		72	208	610	183	128	1201
	%	6.0	17.3	50.8	15.2	10.7	

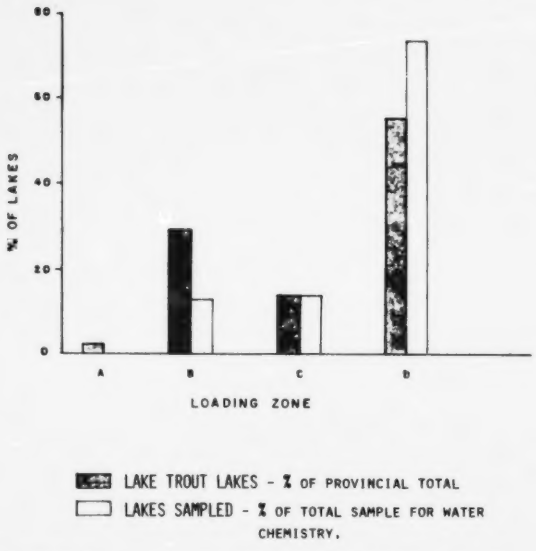

Figure 8. Distribution of lake trout lakes and lakes in extensive data set by loading zone.

Lakes within the Sudbury subzone (watersheds 2C, 2D, 2J) exhibited particularly high sensitivity. For example, in 2D watershed, 39% or 37 of the lakes sampled are already acidified and a further 20% (19) are in the extreme sensitivity class, while in the non-Sudbury subzone most lakes (61%) are in the moderate sensitivity class (Table 6).

The lakes in loading zone B are not particularly sensitive to acidification and the sensitivity of lakes in loading zone C is similar to those in loading zone B with the exception of watershed 2B. In this watershed 4% of the lakes are acidified and 17% are in the extreme sensitivity class.

Distribution of Lakes by pH Class

Although the use of alkalinity classes is a reasonable approach to defining the sensitivity of a waterbody, we have seen that it is the hydrogen ion and associated toxicants (aluminum) to which fish respond. Hence, lakes in the extensive data set were also categorized into four pH classes (<5.0; 5.0 - 5.49; 5.50 - 5.99; $\geq$6.0, Table 7). The pH levels used are epilimnetic summer conditions and may bear little relationship to minimum pH levels that occur during episodic events; hence this categorization results in a conservative estimate of risk to the resource.

Approximately 83% of the lakes sampled had a pH $\geq$ 6.0. With one exception, all lakes in loading zone B were in this pH class as were 94% of the lakes in loading zone C. In loading zone D most lakes also had a pH $\geq$ 6.0 (78%) but the percentages of lakes with pH < 6.0 were elevated compared to the percentages in loading zones B and C. Watersheds 2C through 2K in loading zone D each contributed lakes to pH class 5.50 - 5.99. As in the case of low alkalinity, lakes in pH classes which may affect the health of lake trout populations (<5.0 and 5.0 - 5.49) were mainly confined to watersheds in the Sudbury subzone, 2C, 2D and to a lesser extent 2J.

Estimation of Numbers of Extinct Lake Trout Lakes

The discriminant function combining alkalinity, conductivity and pH was applied to the 1223 lake extensive data set to estimate the number of lakes which are extinct. For this classification, the *a priori* probability of a lake being extinct or viable was set proportional to the representation of extinct and viable lakes in the intensive lake trout lake data set used to derive the function (i.e. 27 of 171 lakes were extinct). Of 1154 lakes with data for all three discriminating variables, 96 or 8.3% were classified as extinct.

It was apparent from examining the data for individual lakes that this function overestimates the number of extinct lakes in the extensive data set. It classified as extinct lakes with water chemistry data (especially alkalinity) outside the range of data used to develop the function.

To circumvent this problem, we repeated the classification with a function derived using pH alone (Wilk's λ = 0.494, χ^2 = 118.72, df = 1, p <0.001) that correctly classified 95.3% of lakes of known population status. This function categorized 59 of 1219 lakes in the extensive data set as extinct (Table 8). Examination of the individual lake chemistry data of lakes of unknown status, revealed no obvious errors.

Extrapolation of Estimates

The description of the current status of sampled lake trout lakes by alkalinity and pH categories and the predicted numbers of viable and extinct lake trout lakes can be extrapolated to the entire Ontario lake trout resource by multiplying the fraction of lakes found within each class in the sample by the total population of lake trout lakes for each watershed (Table 5). The distribution of lake trout lakes within each alkalinity and pH class and the total number of lake trout lakes classified as either viable or extinct are outlined in Tables 9 and 10, and 11, respectively.

We estimate that 80 or 3.7% of lake trout lakes are acidified (alkalinity <0 mg l^{-1}) and that an additional 274 lakes (12.5%) are extremely sensitive (alkalinity 0 - 1.99 mg l^{-1}) to future inputs of acid (Table 9). We

Table 7. pH class of lakes in extensive lake trout lake data set by secondary watershed within loading zones B, C, and D.

Loading zone	Watershed	pH class <5.0	5.0-5.49	5.50-5.99	≥6.0	Total
B	4G	0	0	0	6	6
	5P	0	1	0	107	108
	5Q	0	0	0	39	39
	5R	0	0	0	2	2
	TOTAL	0	1	0	154	155
	%	0.0	0.6	0.0	99.4	
C	2A	0	0	0	48	48
	2B	1	3	6	86	96
	4J	0	0	0	8	8
	4L	0	0	0	8	8
	4M	0	0	0	9	9
	TOTAL	1	3	6	159	169
	%	0.6	1.8	3.5	94.1	
D	2C	2	5	44	224	275
	2D	0	0	1	18	19
	2E	0	1	26	101	128
	2H	0	1	6	90	97
	2J	0	1	1	56	58
	2K	0	1	14	122	137
	2L	0	0	0	3	3
	2M	0	0	0	8	8
	TOTAL	2	9	92	622	725
	%	0.3	1.2	12.7	85.8	
Sudbury	2C	12	6	12	22	52
	2D	23	14	14	43	94
	2J	3	3	8	10	24
	TOTAL	38	23	34	75	170
	%	22.4	13.5	20.0	44.1	
GRAND TOTAL		41	36	132	1010	1219
	%	3.4	3.0	10.8	82.8	

Table 8. Classification of extensive lake trout lake data set.

Loading zone	Secondary watershed	Number viable	Number extinct	Total number	% extinct
B	4G	6	0		
	5P	108	0		
	5Q	39	0		
	5R	2	0		
	TOTAL	155	0	155	0.0%
C	2A	48	0		
	2B	93	3		
	4J	8	0		
	4L	8	0		
	4M	9	0		
	TOTAL	166	3	169	1.8%
D	2C	273	2		
	2D	19	0		
	2E	128	0		
	2H	97	0		
	2J	57	1		
	2K	137	0		
	2L	3	0		
	2M	8	0		
	Subtotal	722	3	725	0.4%
Sudbury[2]					
	2C	38	14		
Subzone	2D	60	34		
	2J	19	5		
	Subtotal	117	53	170	31.2%
	TOTAL	839	56	895	6.2%
	GRAND TOTAL[1]	1160	59	1219	4.8%

[1] Of the 1223 lakes in the extensive data set, 4 had missing data and consequently were not classified.

[2] Sudbury Subzone - between longitudes 8000 and 8130 and latitudes 4600 and 4730.

Table 9. Predicted alkalinity class of Ontario lake trout lakes by secondary watershed within loading zones.

Loading zones	Watershed	Alkalinity class: Acidified	Extreme sensitivity	Moderate sensitivity	Low sensitivity	Not sensitive	Total
B	4G	0	0	17	25	8	50
	5P	0	3	265	75	24	367
	5Q	0	0	90	74	42	206
	5R	0	0	18	18	0	36
	TOTAL	0	3	390	192	74	659
	%	0.0	0.5	59.2	29.1	11.2	
C	2A	0	0	11	50	44	105
	2B	6	26	50	27	37	146
	4J	0	0	0	2	11	13
	4L	0	0	3	5	14	22
	4M	0	0	0	5	16	21
	TOTAL	6	26	64	89	122	307
	%	2.0	8.5	20.8	29.0	39.7	
D	2C	11	81	281	35	10	418
Non-Sudbury	2D	0	3	14	8	0	25
	2E	1	45	85	3	0	134
	2H	0	20	57	26	27	130
	2J	2	8	45	30	12	97
	2K	0	36	148	21	13	218
	2L	0	0	0	0	5	5
	2M	0	0	0	8	15	23
	TOTAL	14	193	630	131	82	1050
	%	1.3	18.4	60.0	12.5	7.8	
Sudbury	2C	16	22	10	3	2	53
	2D	37	19	28	10	0	94
	2J	7	11	4	2	0	24
	TOTAL	60	52	42	15	2	171
	%	35.1	30.4	24.6	8.8	1.1	
GRAND TOTAL		80	274	1126	427	280	2187
	%	3.7	12.5	51.5	19.5	12.8	

Table 10. Predicted pH class of Ontario lake trout lakes by secondary watershed within loading zones.

Loading zones	Watershed	pH class <5.0	5.0-5.49	5.50-5.99	>6.0	Total
B	4G	0	0	0	50	50
	5P	0	3	0	364	367
	5Q	0	0	0	206	206
	5R	0	0	0	37	37
	TOTAL	0	3	0	657	660
	%	0.0	0.4	0.0	99.6	
C	2A	0	0	0	105	105
	2B	2	4	9	131	146
	4J	0	0	0	13	13
	4L	0	0	0	22	22
	4M	0	0	0	21	21
	TOTAL	2	4	9	292	307
	%	0.7	1.3	2.9	95.1	
D	2C	3	8	67	340	418
Non-	2D	0	0	1	24	25
Sudbury	2E	0	1	27	106	134
	2H	0	1	8	121	130
	2J	0	2	2	93	97
	2K	0	2	22	194	218
	2L	0	0	0	5	5
	2M	0	0	0	23	23
	TOTAL	3	14	127	906	1050
	%	0.3	1.3	12.1	86.3	
Sudbury	2C	12	6	12	23	53
	2D	23	14	14	43	94
	2J	3	3	8	10	24
	TOTAL	38	23	34	76	171
	%	22.5	13.5	19.9	44.4	
GRAND TOTAL		43	44	170	1931	2188
	%	2.0	2.0	7.8	88.2	

Table 11. Total number of Ontario lake trout lakes classified as viable or extinct.

Loading zone	Watershed	Total number viable[a]	Total number extinct[b]
B	4G	50	0
	5P	367	0
	5Q	206	0
	5K	37	0
	TOTAL	660	0
C	2A	105	0
	2B	141	5
	4J	13	0
	4L	22	0
	4M	21	0
	TOTAL	302	5
D Non-Sudbury	2C	415	3
	2D	25	0
	2E	134	0
	2H	130	0
	2J	95	2
	2K	218	0
	2L	5	0
	2M	23	0
	Subtotal	1045	5
D Sudbury	2C	39	14
	2D	60	34
	2J	19	5
	Subtotal	118	53
	TOTAL	1163	58
All zones	GRAND TOTAL	2125	63

[a] Total number viable = Total number (Table 5) - Total number extinct.
[b] Total number extinct = % extinct (Table 8) x number of lake trout lakes (Table 5).

predict that 87 lakes (4%) have a pH <5.5 (Table 10) and that lake trout are already extinct in 63 (3%) of the lakes (Table 11). If we remove Sudbury watersheds from consideration because of the large influence of point sources our estimates are considerably lower. We estimate that 20 lakes or 1% of remaining lake trout lakes are acidified, and 26 lakes (1.3%) have pH < 5.5. Ten (<1%) of the non-Sudbury lake trout lakes no longer support lake trout populations.

In summary, we estimate that lake trout are extinct in 3% of Ontario lake trout lakes and that 16.2% of lake trout lakes are currently acidified or extremely sensitive to acidic precipitation. Although these estimates have not been verified and with few exceptions, known cases of lost populations are confined to the Sudbury subzone, we feel that combined with the potential for extinction of unique gene pools, these estimates present a strong argument for continuing work to reduce emissions in order to protect this fragile resource.

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APPENDIX

Appendix A. The Influence of Geology on the Distribution of Ontario Lake Trout Lakes

Lake trout lakes are concentrated in 3 major areas of the province; northwestern Ontario, between the Manitoba boundary northwest of Red Lake, the Minnesota border and Thunder Bay; in central Ontario between Lake Superior in the vicinity of Wawa and the Quebec boundary near Lake Temiskaming; and in southern Ontario on the Algonquin Highlands between Georgian Bay and the middle reaches of the Ottawa River (Fig. 1).

Bedrock Geology

Lake trout lakes are confined almost exclusively to the recently glaciated lakes of the Canadian Shield, with only a few occurring on Paleozoic formations (Fig. 1). The Paleozoic formations are naturally lower in elevation (except for the Niagara escarpment) and relief. The deposition of sedimentary materials by ancient seas had a further levelling effect on the topography. As a result, present day lake basins in extreme Southern Ontario are generally absent or shallow and do not support lake trout. A few exceptions to this generality exist: Lake Simcoe (maximum depth 44 m) and Lake Manitou (maximum depth 30 m) which have size and depth amenable to lake trout; Lake Erie, Lake Ontario and Lake Huron which lie in part or entirely on Paleozoic formations and have, or did have, trout populations; and a few trout lakes on the Hudson Bay Lowlands, the other major Paleozoic region of the province. The four trout lakes lying across the Sutton Ridges occur on a local Precambrian diabase outcrop. In this region hills range up to a few hundred metres above sea level and lakes are up to 85 m in depth.

Topographic Relief

Topographic relief *per se* may be a factor limiting distribution of the lake trout, although relief is determined in part by bedrock geology. For example, lake trout lakes are generally concentrated along the southern margins of the Canadian Shield (Fig. 1), occurring only sporadically in its more central and northern reaches.

In the southern part of the Canadian Shield, which is generally more strongly broken, there are areas of low relief where the lake trout is absent because of the shallowness of the lakes. On the southern margin lake trout lakes are found where the terrain is more broken, for example the La Cloche Mountain area between NE Georgian Bay and Lake Nipissing. Although broken relief generally favours the formation of trout lakes, in extreme cases it may have the opposite effect. This may be the situation across the north and northeastern shore of Lake Superior. The precipitous nature of the watersheds in this area has precluded the formation of impoundments or may have rendered parts of the region inaccessible to the lake trout after glaciation (Fig. 1).

Glacial Activity - Alterations to Lake Basins and Sediments

Lake trout lake distribution in Ontario has also been determined by events in the Pleistocene. At that time glacial activity greatly altered the surficial geology and water patterns of the province and glacial waters no doubt served as major dispersal mechanisms for lake trout. Glacial scour deepened many depressions creating lake trout habitat. The depositions of coarse gravels and rocks created the spawning grounds for the species.

Glacial events may also have served to limit present distribution of the lake trout to some extent. Over a period of thousands of years, deeper parts of glacial lake basins accumulated great deposits of massive and varved clays which had a levelling or filling in effect on the topography. In some areas these clays may be up to 30 m thick (A.N. Boissonneau, pers. comm. to N.V. Martin) and they no doubt served to eliminate some potential lake trout lakes. A secondary effect of these accumulated clays has been the creation of high turbidity in certain lakes, possibly rendering them unsuitable for trout. However, as Wallen (1951) and Van Oosten (1948) have pointed out, turbidity has probably played only a limited role in determining the abundance of most fishes.

Fig. 1 also delineates the broad extent of glacial waters in Ontario and in some areas the nature of their lacustrine deposits (46 N to 52 N in northeastern Ontario and 48 N to 51 N in northwestern Ontario). The boundaries illustrated have been modified from a series of sources, notably Zoltai (1965a, 1965b), Boissonneau (1965a, 1965b) and Prest et al. (1968) and should only be regarded as approximations. The maximum limits of glacial waters are shown and these represent a succession of lakes which occurred at various times over a period of some 10,000 years.

Trout are largely absent from the deeper basins of old glacial lakes; that is the areas of present day massive and varved clays. Only occasional lakes occur in regions of lacustrine sands which represent the shallower water deposits of glacial lakes of long term duration such as Agassiz or Barlow-Ojibway or the main deposits of shorter-lived glacial lakes such as Sultan or Ostrom. Present day lake trout lakes in glacial basins occur specifically on bedrock or outwash areas (eg. south and southwest of Lake Abitibi (glacial Lake Barlow-Ojibway) and Lac Seul (glacial Lake Agassiz)). Trout lakes are also found in regions of ground morainic

tills which have formed a thin mantle over the bedrocks, as in the Kenora-Fort Frances area of Lake Agassiz. Some larger present day lakes lie mainly in regions of massive clays and are consequently shallow but have deeper bays extending into areas of shallower glacial deposits (eg. the western arm of Eagle Lake near Dryden, Bray Bay of Lac Seul and certain bays of Lake of the Woods). Without this filling in process it is possible that many present day lakes between 8 to 15 m in depth would have been deeper (>30 m) and hence provided suitable lake trout habitat.

In summary, the present day distribution of lake trout lakes in Ontario is largely related to the depth of lake basins. This has been determined by topographic relief which had its genesis in the events of the Paleozoic, some 200 to 500 million years ago, and the more recent events of the Pleistocene of some 10,000 years ago.

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97° 96° 95° 94° 93° 92° 91° 90° 89° 88° 87° 86° 85° 84° 83° 82° 81° 80°

56°

55°

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53°

52°

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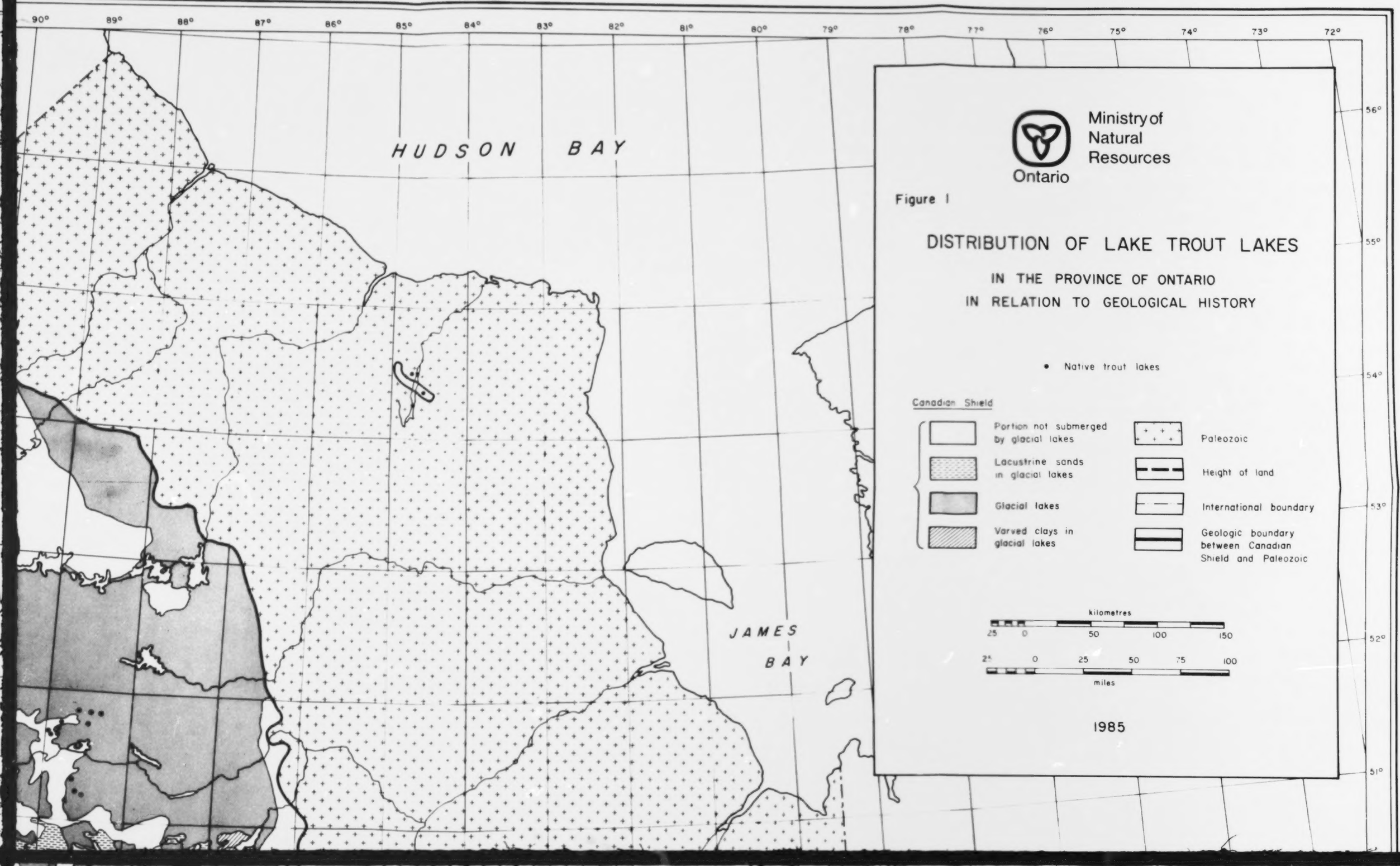
HUDSON BAY

MANITOBA
ONTARIO

LAKE AGASSIZ

MANITOBA

JAME
BA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HUDSON BAY
JAMES BAY
Ministry of Natural Resources
Ontario
Figure 1
DISTRIBUTION OF LAKE TROUT LAKES
IN THE PROVINCE OF ONTARIO
IN RELATION TO GEOLOGICAL HISTORY
• Native trout lakes
Canadian Shield
Portion not submerged by glacial lakes
Lacustrine sands in glacial lakes
Glacial lakes
Varved clays in glacial lakes
Paleozoic
Height of land
International boundary
Geologic boundary between Canadian Shield and Paleozoic
kilometres
25 0 50 100 150
25 0 25 50 75 100
miles
1985

MANITOBA

50°

49°

48°

47°

46°

45°

LAKE OF THE WOODS

LAKE NIPIGON

LAKE SUPERIOR

CANADA
UNITED STATES

LAKE BARLOW-OJIBWAY

L. OSTROM

LAKE SULTAN

ST MARYS R.

NORTH CHANNEL

MANITOULIN ISLAND

GEORGIAN BAY

LAKE NIPIGON

LAKE BARLOW - OJIBWAY

QUEBEC - ONTARIO

LAKE SUPERIOR

CANADA
UNITED STATES

L. OSTROM

LAKE SULTAN

L. NIPISSING

NORTH CHANNEL

St Mary's R.

MANITOULIN ISLAND

GEORGIAN BAY

Ottawa River

St. Lawrence River

50°

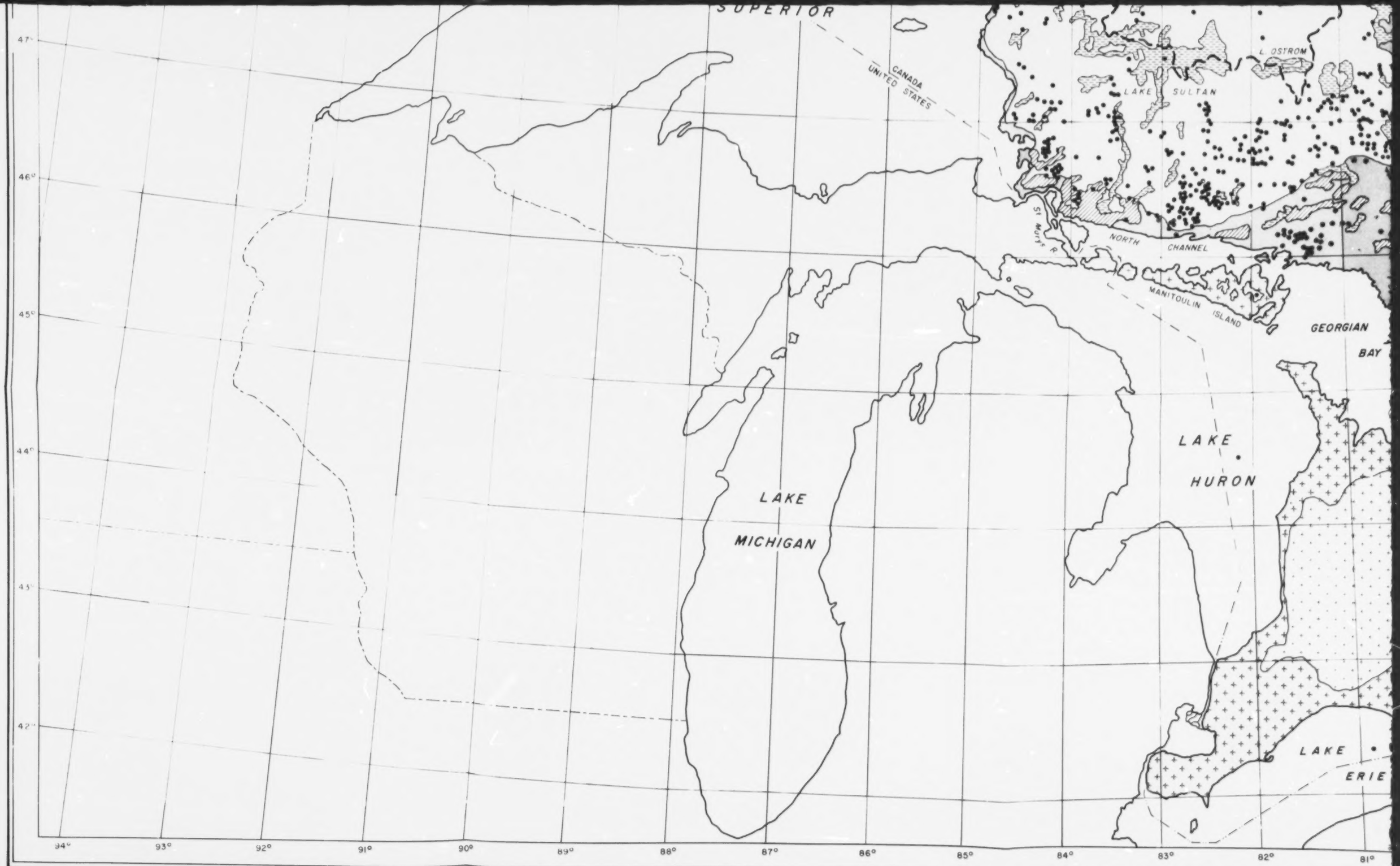
49°

48°

47°

46°

45°


SUPERIOR
CANADA
UNITED STATES
L. OSTROM
LAKE SULTAN
ST MARYS R.
NORTH CHANNEL
MANITOULIN ISLAND
GEORGIAN BAY
LAKE HURON
LAKE MICHIGAN
LAKE ERIE
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CANADA
UNITED STATES

L OSTROM

LAKE SULTAN

St Mary's R.

NORTH CHANNEL

L NIPISSING

Ottawa River

MANITOULIN ISLAND

GEORGIAN BAY

LAKE HURON

LAKE MICHIGAN

SIMCOE

St Lawrence River

LAKE ONTARIO

CANADA
UNITED STATES

LAKE ERIE

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Cartography: P.E.C. Brendon 1983